Submarine-Based Acoustic Doppler Current Profiler (ADCP) Measurements of the Upper Arctic Ocean

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LONG-TERM GOALS

My long-term goals are to better understand and quantify the processes that are primarily responsible for redistribution of heat and salt within the Arctic Ocean. My topical focus has been on quantification of the slope-trapped boundary currents and on understanding the roles of small-scale and mesoscale processes in the redistribution of water properties within the central basins. My geographical focus spans the Arctic Basin but emphasizes the Nansen, Amundsen and Makarov basins and the frontal systems that overlie the interbasin ridges.

OBJECTIVES

Four primary objectives contribute to the above goals.

- Improve the present understanding of mean circulation patterns in the Arctic, with a focus on the topographically controlled boundary currents that redistribute heat and salt.
- Quantify the speeds, heat, salt and mass transports associated with the boundary currents.
- Improve our understanding of the nature, distribution and dynamics of upper ocean mesoscale eddies and frontal systems, and assess their role in the transport of heat and salt.
- Assess the roles of turbulent mixing and double diffusion in redistributing heat and salt, with an emphasis on the impact of these processes on the halocline.

APPROACH

I approach the above goals through analyses of recently collected field data. The core dataset has been collected from submarine deployments in 1995, 1996, 1997, 1998 and 1999. These data span the entire Arctic Ocean and include temperature (*T*), salinity (*S*), dissolved oxygen (*DO*) and upper ocean currents. These data are supplemented with *T*, *S* and current data collected during 1993, 1995 and 1996 cruises of the German research icebreaker *Polarstern*, with data from the 1994 US/Canadian trans-Arctic section, and from an array of instrumented moorings that were deployed off the Siberian continental slope from 1995-1996. Data analysis methods include water mass and time series analyses and intercomparisons among the data and a broad variety of analytical and numerical model results. At present, I am focussing on a small number of specific process-related problems while at the same time working toward an integration of the several datasets that should help to provide a holistic view of the Arctic Ocean, its primary circulation and significant internal processes.

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WORK COMPLETED

The current year began directly following my participation in the extensive summer 1998 deployment of the submarine *Hawkbill*. Work completed during this year has consisted largely of a preliminary assessment of the summer 1998 dataset and of efforts to integrate the several datasets that are listed above. A primary objective has been to attempt a better definition and quantification of major Arctic Ocean circulation features. A second objective has been to construct a large scale "climatology" of the ubiquitous double diffusive *T* and *S* inversions seen in the Arctic Ocean in order to gain a better understanding of their physical cause and to assess their impact. To stimulate thought, a seminar presenting an overview of SCICEX basin-wide results was presented at the Institute of Ocean Sciences in Canada, and subsequent discussions were held with E. Carmack and others of IOS. An expanded version of the seminar was presented to European colleagues as an invited talk at the XXII General Assembly of the IUGG in Birmingham, UK during July [*Muench*, 1999]. A manuscript describing eastern Arctic currents within the context of basin-scale processes is being prepared jointly with R. Woodgate and K. Aagaard of the University of Washington, and with others, and is nearing completion prior to planned submission to *Deep-Sea Research*. A related poster has been submitted for presentation at the January 2000 AGU Ocean Sciences Meeting [*Woodgate et al.*, 2000]. A manuscript relating river tracers to large-scale upper ocean circulation, with C. Guay as lead author, is nearing completion and will be submitted to *JGR*. Finally, work continues with U. Schauer, B. Rudels and others on manuscripts describing physical conditions observed during the 1995 and 1996 *Polarstern* cruises to the eastern Arctic [*Rudels et al.*, 2000, and work in progress].

Process-specific SCICEX results dealing with mesoscale eddies and frontal features were presented as posters at the Fall 1998 AGU meeting in San Francisco [*Muench et al.*, 1998], at the Second Gordon Conference on Polar Oceanographic Processes in Ventura during March 1999, and at the July IUGG General Assembly in Birmingham [*Muench et al.*, 1999]. A manuscript describing and discussing a cold core eddy observed during the 1997 SCICEX deployment is nearing readiness for submission to *Journal of Geophysical Research*.

Quantitative results on upper ocean mixing continue to be addressed. Results from the 1993 and 1995 *Polarstern* cruises have been published in *Dewey et al.* [1999]. Results from the 1996 *Polarstern* cruise and from selected SCICEX submarine data are at present being integrated with the earlier data for future publication.

An evening meeting was held in Seattle during July 1999 with U. Schauer and R. Dickson for the purpose of discussing possible relationships among observed interannual changes in the Arctic and those in the ocean farther south. Soon afterward, I co-convened an interassociation symposium on "Atmosphere and ocean connections between the polar regions and lower latitudes" at the IUGG General Assembly.

RESULTS

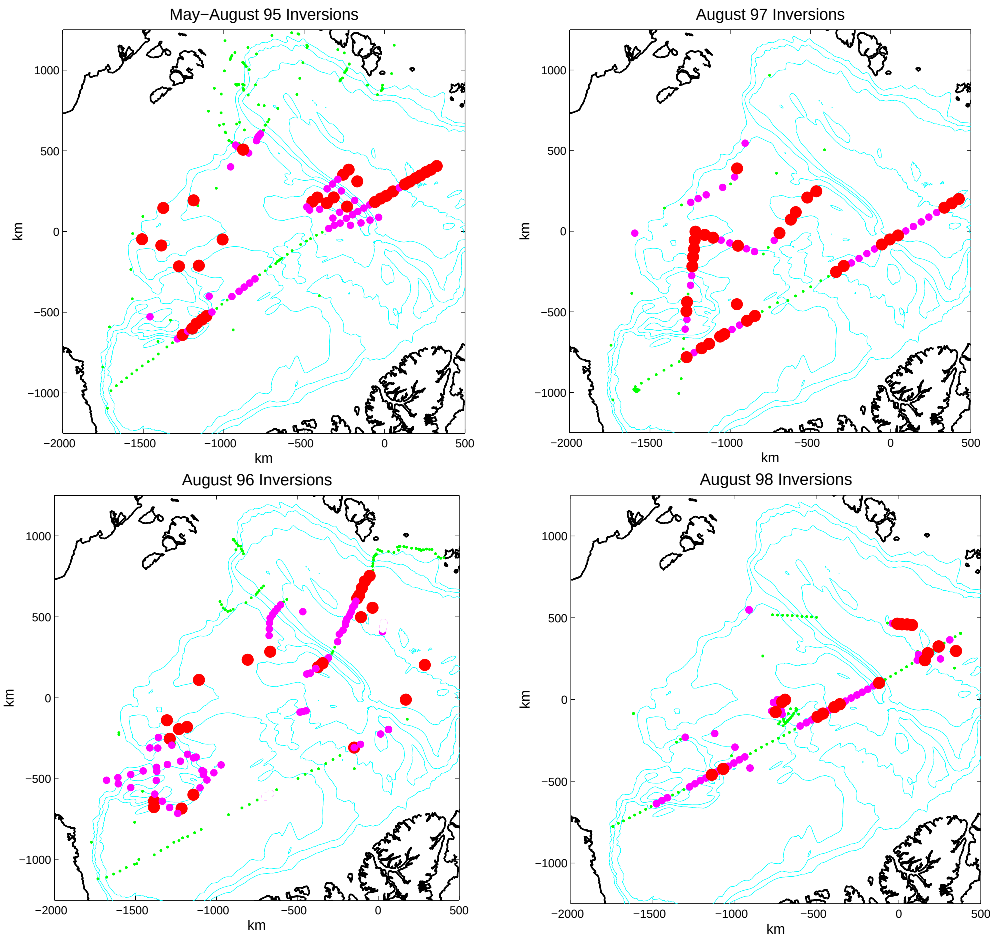
Analysis of data from a cold core eddy observed during the 1997 SCICEX deployment has revealed that the core was comprised primarily of Pacific water [*Muench et al.*, 1998, and work in progress]. The eddy structure is consistent with formation in association with coastal polynya formation in the Chukchi Sea as modeled by *Chapman* [1999]. This result substantiates that convective events have recently occurred in the western Arctic and have penetrated to the lower pycnocline. Additionally, it supports conjectures [e.g. *Smethie et al.*, 1999] that Canada Basin waters are modified by admixture of water that is transported into the region by eddies.

Year-long current measurements obtained from moorings deployed on the continental slope near the Siberian end of the Lomonosov Ridge have allowed quantification of the slope boundary current in that region [*Woodgate et al.*, 2000, and work in progress]. The current, which is strongly barotropic, splits into two roughly equal branches when crossing the Ridge, one branch continuing east along the slope and the other veering north along the Ridge. Strong eddies were present and were most frequent west of (upstream from) the Ridge. These eddies were consistent with formation either in association with convective events in the adjacent shelf seas or through instability mechanisms associated with the Barents Sea inflow to the Arctic Ocean.

Combined time-series *T* and *S* data from the moorings and station data from *Polarstern* have provided insight into the effects of the Barents Sea inflow on the upper layers of the eastern Arctic Ocean [*Woodgate et al.*, 1999, *Rudels et al.*, 2000, and work in progress]. Sudden changes in the upper ocean from the warm Atlantic layer upward through the halocline near the Lomonosov Ridge can be traced west to the site where Barents Sea waters enter the Arctic Ocean. The Barents Sea inflow and its subsequent distribution within the Arctic Ocean strongly impacts the eastern Arctic halocline. The rate at which ice flows from the Arctic Ocean into the Barents Sea can influence the halocline, hence the stability of the eastern Arctic Ocean ice cover, through a feedback mechanism. Since the sea ice responds directly to atmospheric forcing, this mechanism provides a means by which the upper ocean in at least the eastern Arctic can be influenced by climatological changes.

A preliminary attempt at synthesis of these results leads to a conceptual description of the processes that determine distributions of heat and materials in the Arctic Ocean [*Muench*, 1999]. The continental boundaries are dominated by advection due to primarily barotropic, slope-trapped currents. Mean speeds associated with these currents are a few cm/s. Continuations of these currents persist northward along the several major mid-ocean ridge systems that cross the central basins, but these northward extensions may be discontinuous where gaps occur in the ridges. Isolated regions of high topography occur along the ridges, and these are probably sites for local closed circulation cells, perhaps having the nature of Taylor columns. In some regions where the ridges are highly discontinuous and characterized by steep bottom topography, such as the Arctic Mid-Ocean (Nansen-Gakkel) and Alpha-Mendeleyev systems, the currents break up into filaments and eddies. The recent conceptualization of Arctic Ocean circulation as a set of bathymetrically-trapped cyclonic gyres is judged based on these results to be valid in an overarching sense but probably inaccurate in many of the details.

Away from the slope- and ridge-trapped currents, transport and mixing of properties appear to be driven in large part by mesoscale eddies and through double-diffusion. Conditions appropriate to deep eddy formation are present only off the Santa Anna Trough where Barents Sea water enters the Arctic Ocean. Upper ocean eddies form off Alaska where the Alaskan Coastal Current rounds Point Barrow, and can presumably form in association with coastal polynyas in any of the shelf sea regions. The *T* and *S* inversions symptomatic of double diffusion occur across the Nansen, Amundsen and Makarov basins and are most pronounced near the ridges that separate these basins (see Figure). We expect, based on theoretical results, that these processes result in horizontal transport of heat and salt. The features have not been detected in the Canada Basin or over the Alpha Rise, however, upper ocean eddies that originate off Alaska are more common at least in the Canada Basin than in the eastern Arctic. Tracer studies have suggested that the least well ventilated waters in the Arctic occur over the Alpha Rise, consistent with these conjectures. Recent theoretical work has shown that inversions resembling these can occur in association with frontal systems [*Hebert*, 1999, *May and Kelley*, 2000]. Indeed, they are most pronounced near the ridge-associated frontal systems within the Arctic Ocean (see Figure). The bathymetric features then lead indirectly, through control over the mean flow, generation of fronts, and development of associated double-diffusive features that then spread laterally into the central basins, to water mass ventilation and modification in the central basins.



Locations where double diffusive inversions were observed during 1995-1998 from* Polarstern *and from* SCICEX *submarines. Red (large) dots show well-developed inversions, magenta (mid-sized) dots depict degenerate inversions, and green (small) dots indicate that no inversions were present. Isobaths based on the ETOPO5 dataset are shown at 1000 m intervals. The best developed inversions occur in association with frontal systems that overlie the major ridge systems and the Chukchi Rise, and may also serve as markers for recent change as in the Makarov Basin. Inversions were conspicuously absent from the Canada Basin and Alpha Rise segments of the western Arctic, reflecting perhaps a lack of sufficiently strong gradients to lead to formation of the features.

IMPACT/APPLICATIONS

The integrated Arctic Ocean dataset being used in this research covers nearly a decade – more than a decade if the 1987 *Polarstern* and 1991 *Oden* data from the eastern Arctic are included. Results of analyses of data over this time span are expected to provide significant insight into the nature of the observed interannual water column changes and their physical linkages with other global climate systems. Inasmuch as these systems are interactive, analyses based upon an integrated, decade-length database can help us to assess the role of the Arctic in global climate change. Additionally, results from the analyses of the double-diffusive inversions are expected to provide new insight into double diffusive processes elsewhere in the global ocean.

TRANSITIONS

Results of the ongoing work, especially current speeds and quantitative information concerning mixing, are being provided to numerical modelers to help in parameterization and validation of models over a variety of scales. For example, information on the eddy reported by Muench et al. [1998] has been provided to D. Chapman and G. Gawarkiewicz of Woods Hole Oceanographic Institution because their shelf polynya model predicts formation of just such eddies. Current data and mixing parameters are being provided to W. Maslowski of the Naval Postgraduate School for use in development of his basin-scale GCM. Detailed assessments of interannual changes in T and S are of direct pertinence to research, such as that of M. Holland of NCAR, that relates to coupling between Arctic and global climate changes. Large-scale distribution and interannual changes in double diffusive features have proven to be of interest to theoreticians, such as B. Ruddick of Dalhousie University, who are addressing small-scale mixing processes. Finally, the information being obtained through analysis and integration of the existing data is proving to be invaluable in planning activities related to the ARCSS Shelf-Basin Interaction (SBI) and SEARCH programs.

RELATED PROJECTS

Results on upper ocean mixing processes are being directly integrated with results being obtained from the Weddell Sea AnzFlux (Antarctic Zone Fluxes) and international DOVETAIL (Deep Ocean Ventilation Through Antarctic Intermediate Layers) programs. The integrated results will provide information on the relations among wind-driven surface currents, tidal currents, sea ice cover, upper ocean stratification and mixing processes over a spectrum of parameter values that typify high latitude oceans.

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